LongTerm Settlement by Seismic

by Pit-18 2014

Application of Wavelet Spectrogram Analysis of Surface Waves for Long-term Settlement Prediction

Sri Atmaja P. Rosyidi
Department of Civil Engineering, Universitas Muhammadiyah Yogyakarta

Colin Peter Abbiss
3, Marea Meadows, Heacham, Kings Lynn, Norfolk, PE31 7SR, UK

ABSTRACT: Wavelet spectrogram analysis of surface waves (WSASW) method has been introduced and recently implemented to improve the field measurement of shear wave velocity and damping ratio on soil sites. This method improves a common used signal processing tools, e.g., Fourier analysis, for attenuation analyses which fail to identify when certain characteristic features occur in a waveform. The time-frequency character of wavelet transforms allows increased flexibility as both traditional time and frequency domain system identification approaches can be exploited to examine nonlinear and non-stationary seismic events that are in essence obscured by traditional spectral approaches. This paper presents application of wavelet spectrogram analysis of surface waves method for simultaneous shear wave velocity, damping ratio and long-term settlement calculation on soft clay. Soil model is treated as an elastic material of viscoelastic property. The calculated elastic settlement from shear wave velocity and its corresponding shear modulus, and equivalent damping are then used to calculate the long-term settlement by applying the generalised viscoelastic formula. Comparisons to traditional methods of settlement predictions were made and the viscoelastic formula has shown better agreement to the observed settlement.

Keywords: long-term settlement, shear modulus, shear wave velocity, wavelets, damping

1 INTRODUCTION

The surface wave measurement is one of in-situ seismic methods based on the dispersion of Rayleigh waves (R-waves) which is used to determine dynamic soil properties, i.e., the shear wave velocity (V_S), shear modulus (G), damping ratio (D) and depth of each layer of the soil profile. Much of the basis of the theoretical and analytical work of this method for soil investigation has also been developed (Stokoe et al., 1994). In surface wave measurements, the application of wavelet analysis has been started by Kim and Park (2002) who used a harmonic wavelet transform for determining dispersion curve in the spectral analysis of surface wave (SASW) method. Their results showed that a new procedure based on wavelet transform was proposed for calculating the phase and group velocities at each frequency independent of remaining frequency components using the information around the time at which the signal energy. The method was also less affected by noise and near field effect than the phase unwrapping method that used as a common procedure in the surface wave measurement. In addition, Shokouhi et al. (2003) explained the advantages of the wavelet approach in the SASW measurement, i.e., detection and characterization of cavities and objects buried in the ground and characterization of layer interfaces, with respect to layer dipping and abrupt interface changes. Wavelet spectrogram analysis of surface waves (WSASW) is one of improved surface waves technique has been introduced by Rosyidi (2009).

The aim of this study is to introduce the capability of in-situ surface wave measurement of the wavelet spectrogram analysis of surface waves (WSASW) technique for long-term settlement measurement. This technique has capability to reconstructed spectrograms of noisy seismic waves and produces the enhanced phase velocity dispersion curve. In soft soil site, the environmental noises are dominant in the recorded seismic signals due to the wave frequency of interest are identical to the frequency level of noisy signals.

2 RESEARCH METHOD

2.1 *Location of Study*

In this research, a test site at Radio Televsyen Malaysia (RTM), Kelang, Malaysia was selected as location of measurement. The site is generally an original ground and the soil mass is mainly of greyish clay. The regional geology of the site has been classified as recent quaternary of dominantly alluvial deposits of soft marine clay with traces of organics. The soil descriptions from the observed boreholes at the location have shown that the soil type found were quite similar with the geology classification, i.e. greyish clay with decayed wood at most of the soil layers of the subsoil stratum.

2.2 *Field Measurement*

In this study, the seismic signal data were collected by using the SASW field measurement set up. There are three important set ups in the SASW measurement for soft soil location, i.e., adequate wave frequencies produced from the various impact sources, capability of receivers or geophones to receive the interested frequency and the appropriate acquisition unit or spectrum analyser used in the measurement. A set of impact hammer sources of various frequencies were used to generate R waves on the soil surface. The propagation of the waves was detected using two receiving geophones and the analog signals were then transmitted to a spectrum analyzer which consisted of acquisition box and transferred digitally to a notebook computer (Figure 1).

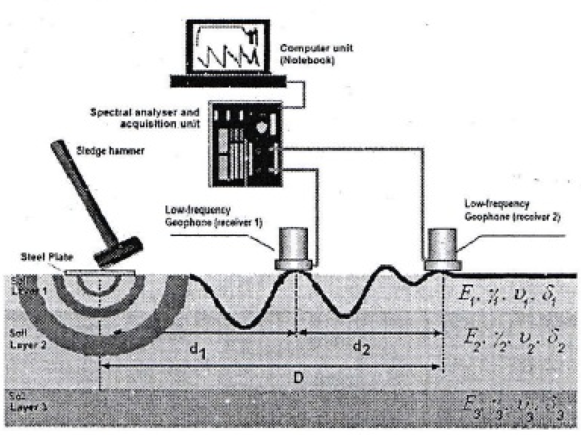

Figure 1. SASW measurement setup applied on the soil sites

2.3 *Procedure of Data Analysis*

A procedure of data analysis for the WSASW technique is discussed in the following section.

1. Seismic data are recorded from field measurement and transferred to computer on digital data.

2. Select the wavelet function and a set of scale, s, to be used in the wavelet transform. The different wavelet function may influence the time and frequency resolution. In this study, a Morlet wavelet function was selected as a mother wavelet in the CWT filtering.

3. Develop the wavelet scalogram by implementing the wavelet transform using computed convolution of the seismic trace with a scaled wavelet dictionary. Scalogram is a local time-frequency energy density which measures the energy of the signals in the Heisenberg box of each wavelet. Wavelet scale is calculated as fractional power of 2 using the formulation (Torrence & Compo, 1998):

$$s_j = s_0 2^{j\delta_j}, j = 0, 1, ..., J \quad (1)$$

$$J = \delta j^{-1} \log_2\left(\frac{N\delta_t}{s_0}\right) \quad (2)$$

   where, s_0 is smallest resolvable scale = $2\delta_t$, δ_t is time spacing, and J is largest scale.

4. Convert the scale dependent wavelet energy spectrum (scalogram) of the signal to a frequency dependent wavelet energy spectrogram in order to compare directly with Fourier energy spectrum.

5. Perform the CWT filtration on the wavelet spectrogram by obtaining the time and frequency localization thresholds. Wavelet spectrogram is developed from the scalogram which allows the filtration technique implemented directly to the spectrum. In this study, the CWT filtration was developed by a simple truncation filter concept which only considers the passband and stopband. The interested spectrum of signals are to be passed when the spectrum energy is maintained in original value. A design of the CWT filtration is proposed by Rosyidi (2009).

6. The value of 1 means the spectrum energy is passed and the value of 0 represents the filtration criteria when the spectrum energy is set as 0.

7. Reconstruct the time series of seismic trace using :

$$f(t)=\frac{1}{C_\psi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}F_W(\sigma,\tau)\psi\left(\frac{t-\tau}{\sigma}\right)\frac{d\sigma}{\sigma^2}\frac{d\tau}{\sqrt{\sigma}} \tag{3}$$

$$C_\psi=2\pi\int\frac{|\hat{\psi}(\omega)|^2}{\omega}d\omega<\infty \tag{4}$$

Where σ is the dilation parameter or scale and τ is the translation parameter (σ, τ ∈ ℜ and σ ≠ 0), $\hat{\psi}(\omega)$ is the Fourier transform of ψ(t). The integrand in equation 4 has an integrable discontinuity at ω = 0 and implies that $\int\psi(t)dt=0$.

8. Calculate the phase different from reconstructed signals at each frequency to develop the phase spectrum for the experimental dispersion curve. The phase data can be calculated from:

$$\phi_n(s)=\arctan\left(\frac{\Im\{s^{-1}W_n^{XY}(s)\}}{\Re\{s^{-1}W_n^{XY}(s)\}}\right) \tag{5}$$

where,

$$W_n^{XY}(s)=W_n^X(s)W_n^{Y*}(s) \tag{6}$$
$$= \text{wavelet cross spectrum}$$

9. By extracting the data of the phase angle from the phase spectrum, a composite experimental dispersion curve can be calculated by the phase difference method. The time of travel between the receivers for each frequency can be calculated by:

$$t(f)=\frac{\phi(f)}{(360f)} \tag{7}$$

Where, f is the frequency, $t(f)$ and $\phi(f)$ are, respectively, the travel time and the phase difference in degrees at a given frequency. The distance of the receiver (d) is a known parameter. Therefore, the Rayleigh wave velocity, V_R or the phase velocity at a given frequency is simply obtained by:

$$V_R=\frac{d}{t(f)} \tag{8}$$

By repeating the procedure outlined above and using equation 7 and 8 for each frequency value, the experimental dispersion curve is subsequently generated.

10. An inversion analysis was used to generate the shear wave velocity profile. In the inversion process, a profile of a set of a homogeneous layer, extending to infinity in the horizontal direction was assumed. The last layer is usually taken as a homogeneous half-space. Based on the initial profile, a theoretical dispersion curve was constructed using an automated forward modeling analysis involving 3-D dynamic stiffness matrix method (Rosyidi, 2009).

11. The soil shear modulus profile can be obtained by linear elastic model involving the parameter of the shear wave velocity obtained from inversion process as mentioned in previous section. The soil shear modulus is calculated from the following equation:

$$G=\frac{\gamma V_S^2}{g} \tag{9}$$

where, G = the dynamic shear modulus, V_S = the shear wave velocity, g = the gravitational acceleration; and γ = the total unit weight of the material.

12. In order to measure the attenuation data from signals recorded from field measurement, the spectrogram attenuation model developed by Rosyidi (2009) was employed in the analysis (Equation 10). The decrease in amplitude (energy density) of the vertical component of the R-wave with distance due only to geometric configuration is also called the radiation damping or geometric spreading. An effective soil damping ratio of R-wave in layered medium can be defined from the attenuation analysis and the value is frequency dependent. The attenuation data (α) of R-wave can be performed by the spectrogram attenuation model proposed by Rosyidi (2009) as follows:

$$\ln\left[\frac{W_f^{R_2}(u,s)}{W_f^{R_1}(u,s)}\right]=\ln\left[\left\{\frac{R_1}{R_2}\right\}^{n}\{G(R)\cdot G(I)\cdot K(R)\}e^{\{-\alpha(f)(R_1-R_2)\}}\right] \tag{10}$$

where, R_1 dan R_2 = geophones distance from the sources (if using two geophones),

$W_f^{R_1}(u,s)$ dan $W_f^{R_2}(u,s)$= spectrogram magnitude response for geophone 1 and 2 respectively, $G(R)$ = geometric spreading factor, $G(I)$ = instrumentation correction factor and $K(R)$ = correction for refracted and transmitted waves.

Finally, the experimental attenuation curves can be used in the inversion process aimed at estimating the variation of soil shear damping ratio with depth. The inversion process is carried out using the SURF code (Herrmann, 1994). Experimental attenuation curve consists of surface-wave attenuation data at different frequencies obtained from Equation 10.

13. Conduct hammer damping measurements to obtain the average damping and quality factor. Q defined as:

$$Q = \frac{\pi}{\ln\left(A_1/A_2\right)} \tag{11}$$

where, A_1 and A_2 are the corresponding amplitude damping of the wave.

14. An equivalent measured quality factor, Q, can also be obtained from the plate load test. The average value of the adopted Q can be taken from several unload-reload cycle results, defined as :

$$Q = \frac{\Delta W}{4\pi W} \tag{12}$$

where ΔW = work done (area of the loop) and W = energy stored (area of triangle of linear stress-strain plot)

15. Calculate the elastic settlement, w_o due to the loading on site using the Brown and Gibson chart (1972) as illustrated in Figure 2.

16. Calculate the equivalent elastic strain due to elastic settlement from No. 15.

17. Calculate the strain, ε due to the settlement of the pad

$$\varepsilon = \frac{w}{2b} \tag{13}$$

where, b = pad equivalent radius, w = settlement of pad

18. Calculate the characteristic strain (ξ_C),

$$\xi c = \left(\frac{2\xi}{e-1}\right)\left(\exp\left(\frac{D_{\max}}{D}-1\right)-1\right) \tag{14}$$

where, D = measured damping, $D_{\max}$ = maximum damping (0.33), ξ = strain measured at measured damping, D

19. Calculate the damping at the elastic strain (D):

$$D = \frac{D_{\max}}{\left(1+\ln\left(1+(e-1)\left(\frac{\xi c}{2\xi}\right)\right)\right)} \tag{15}$$

20. Calculate the elastic settlement, primary and secondary settlement, w for period of time t :

$$w = w_o\left(\frac{t}{t_o}\right)^{4D/\pi} \tag{16}$$

where, w_o = elastic strain from Brown and Gibson (1972), t = settlement time of interest, t_o = period of seimic measurements (*1/frequency*).

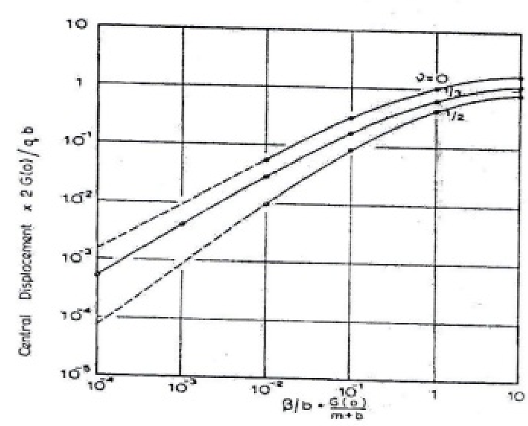

Figure 2. The factor of elastic deformation from Brown and Gibson (1972)

3 RESULTS AND DISCUSSION

3.1 *Shear Wave Velocity Profile*

The actual shear wave velocity of the soil profile is produced from the inversion of the experimental dispersion curve. In the inversion process, a profile of a homogeneous layer extending to infinity in the horizontal direction is assumed. An example shear wave velocity profile of soil site from this study is shown in Figure 3. The average inverted shear wave velocity of soil layer for RTM Kelang test sites was found to be 54.90 m/s with a range of 38.52 to 103.53 m/s. Using the shear wave velocity parameter, the soil material in this study could be evaluated and classified as soft clay (marine clay). The result shows that the soil classification based on the shear wave velocities is also reasonably in agreement with the laboratory tests.

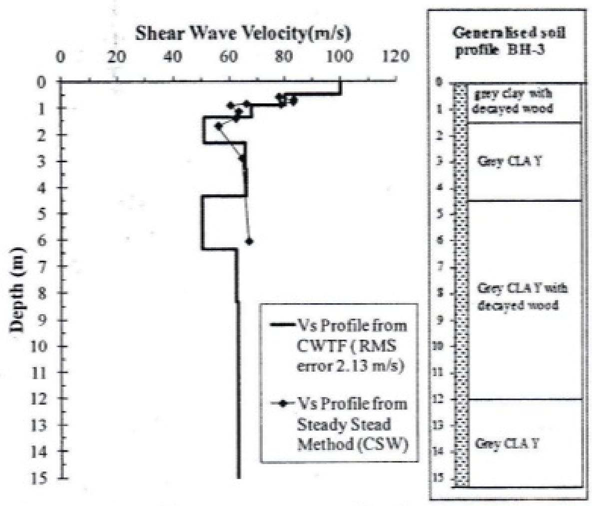

Figure 3. Shear wave velocity profile and comparison with the borehole log

3.2 *Settlement Prediction*

The values of shear wave velocity from inversion analysis of the WSASW test are used in order to calculate the long-term settlement at Klang. Results of the total settlement at observed BH at the location of study and its corresponding time are given in Figure 4 calculated from the shear wave velocity parameter of 50.2 m/s at the depth of 1.86 m (at observed depth in settlement) of the WSASW method. In this calculation, the results of damping ratio obtained from the hammer damping method was found to be 15 % with of the characteristic strain (εr) was found to be 0.00025 that represents a strain level at which the largest change in damping as a function of strain was found. Its value is recommended to be used in the long-term settlement calculation of the seismic method. The spreadsheet of settlement calculation is summarised in Table 1.It was found that the 24 hours immediate settlement from WSASW method for observed BH is estimated to be 25.75 mm, while the corresponding total long term settlement of 300 days is estimated to be 54.13 mm.

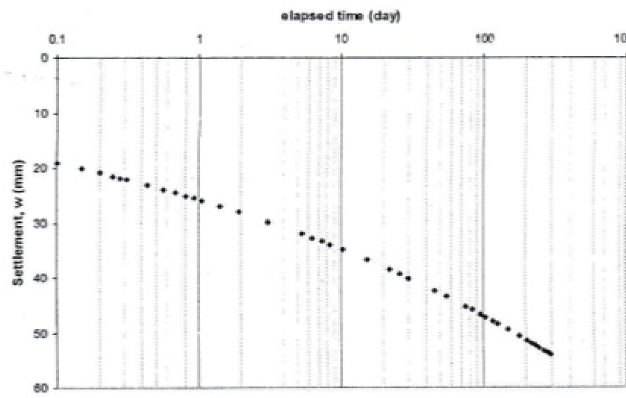

Figure 3. Settlement with time from WSASW results

Table 1. Spreadsheet for settlement calculation vs time from the WSASW method

Time (days)	log t (days)	$(t/t_o)^{(4D/\pi)}$	total *w* (mm)
0.1	-1	4.633	19.080
0.2	-0.698	5.071	20.883
0.3	-0.505	5.374	22.133
0.4	-0.359	5.615	23.125
0.5	-0.249	5.802	23.894
0.8	-0.0901	6.086	25.066
2	0.2872	6.816	28.070
3	0.491	7.247	29.848
5.	0.726	7.777	32.028
10	1.014	8.476	34.909
15	1.185	8.923	36.750
103	2.015	11.444	47.130
127	2.102	11.748	48.382
180	2.255	12.299	50.650
204	2.310	12.503	51.490
267	2.427	12.950	53.331
296	2.471	13.123	54.046

3.3 *Comparison with Other Predictions*

Prediction of consolidation settlement in the one-dimensional method was applied by using the procedures of Traditional Terzaghi method (Terzaghi and Peck, 1967) and two modified Terzaghi methods, i.e. Skempton-Bjerrum (Bjerrum, 1972) and Modified Terzaghi (Coduto, 1994) methods based on laboratory tests data.

Table 2. Input parameters for consolidation settlement prediction of Terzaghi, Skempton-Bjerrum and Coduto method based on laboratory data

Parameters	Layer No.					
	1	2	3	4	5	6
Density, γ (kN/m^3)	12.795	13.034	13.136	13.112	13.563	14.114
Initial void ratio, e_o	3.183	2.984	2.903	2.955	2.759	2.455
Compression index, C_c	1.379	1.324	1.381	1.459	1.401	1.296
Pore pressure parameter, A	0.524	0.548	0.590	0.685	0.854	0.909
Overconsolidation ratio, OCR	2.088	1.868	1.711	1.623	1.401	1.286
3-dimensional adjustment factor, ψ	0.630	0.647	0.660	0.667	0.684	0.693
Coefficient of consolidation, c_v (m^2/day)	0.0026	0.0033	0.0036	0.0038	0.0042	0.0044

In the prediction of consolidation settlement which is based on the laboratory data, the subsoil is divided into 6 soil layers as the BH results from site investigation. Table 2 shows the input parameters of consolidation settlement prediction methods.

Figure 4 shows the predicted and measured settlement with time. The results have shown that the predicted settlement obtained from seismic methods (WSASW) had given better predictions of settlement where their calculations were found to be closer to the monitored settlement observed at BH. The parameters of shear wave velocities that are the main input in the seismic method are taken from the WSASW measurement and the comparison method of continuous surface waves (CSW) measurement. The Terzaghi (Terzaghi and Peck, 1967), Skempton-Bjerrum (Bjerrum, 1972) and Modified Terzaghi (Coduto, 1994) methods had given relatively conservative predictions of long term settlement with time as observed at BH, although the immediate settlement of less than 24 hour, were found to be closer to the monitored settlement. After about 10 days, the total predicted settlement from the traditional methods became larger with observed deviation with time. The statistical parameters of RMS error and ratio of difference were calculated for the predicted settlement methods used in this study compared to the monitored settlement. The RMS error of predicted data of settlement from WSASW, CSW, Terzaghi, Modified Terzhagi (Coduto) and Skempton-Bjerrum calculation compared to the observed data of settlement at observed BH is illustrated in Figure 5. As mention before, conventional methods were found to fit better with the monitored settlement with elapsed time below 10 days where values the of the RMS error were found to be less than seismic methods. After about 20 days, the RMS error for these methods increases and then showed larger deviation to the final observation as compared to the monitored settlement.

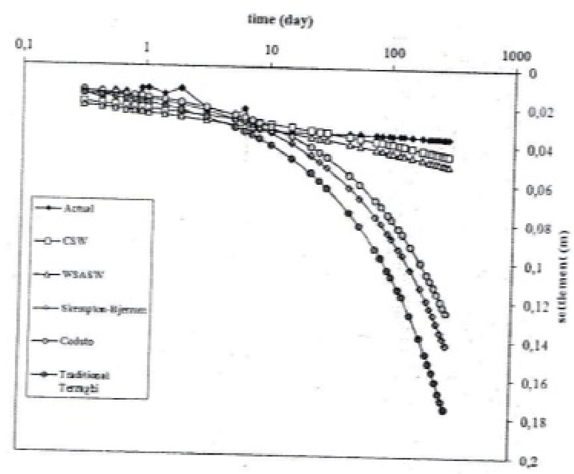

Figure 4. Comparison between predicted and measured settlement at observed BH

3.4 *Sensitivity Analysis for Shear Wave Velocity in Settlement Prediction*

The aim of sensitivity analysis is to assess the relative important once of the parameters influencing the settlement prediction calculation using the seismic method. The seismic parameters included in the sensitivity analysis are the shear wave velocity (V_S), damping ratio (D) and density (ρ).

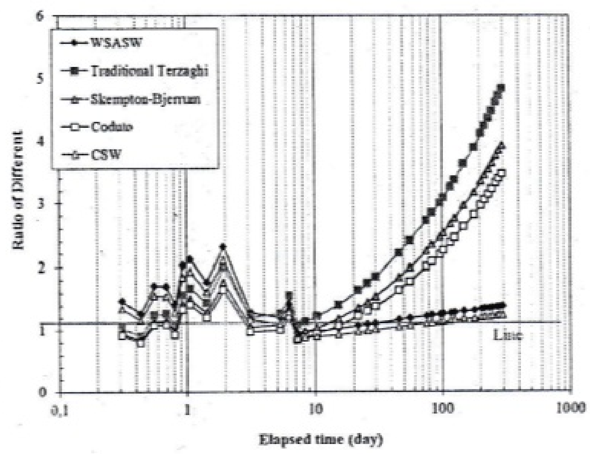

Figure 5. RMS error of predicted settlement

Those parameters are obtained from the variables that are used in equation of the seismic settlement calculation. The shear wave velocity and density parameters are used to calculate the shear modulus and are related to the elastic deformation of soft soil which is written as:

$$w_0 = \frac{fqb}{2G_0} \tag{17}$$

where f is factor from Brown and Gibson (1972) graph which is presented in Figure 2, b is a radius of footing, q is amount forces of loading which is applied to the ground surface and G_0 is an initial shear wave velocity which is obtained from:

$$G_0 = \rho V_S \tag{18}$$

In this sensitivity analysis, a correlation analysis of the parameters involved in the settlement calculation was carried out to measure the level of significant of each parameter. The parameter used in the correlation analysis is the coefficient of correlation (r) having values ranging from 0 to 1. The value of one describes a very significant correlation and vice versa.

Table 3 shows the result of correlation analysis on shear wave velocity, damping ratio and density. The parameter of Shear wave velocity has a significant effect for the total calculated settlement, while damping and density have shown insignificant effect on the total calculated settlement. Vs parameter as compared to the other parameter was found to have the values of correlation of regression (r) closest to 1, indicating that the values are of significance relationship. While damping ratio and density were found to be having values of "r" closed to 0, indicating that insignificant relationships to the total settlement value. Negative signs of the independent variables indicate that the relationship of the dependent and independent variable is inversed, with increasing independent variable followed by decreasing dependent variable while positive signs of the independent variables show otherwise.

Table 3. Correlation analysis of shear wave velocity, damping ratio and density to the settlement calculation

Observed time	Shear wave velocity (r)	Damping (r)	Density (r)
24 h	-0.6284	0.0234	-0.0450
200 h	-0.6153	0.0240	-0.0449
1000 h	-0.6062	0.0241	-0.0448
2000 h	-0.6025	0.0240	-0.0448
5000 h	-0.5978	0.0238	-0.0447
6500h	-0.5965	0.0237	-0.0447

4 CONCLUSIONS

This paper presents the capability of surface wave measurement using the Wavelet Spectrogram Analysis of Surface Waves (WSASW) for long term settlement prediction on soft clay. The seismic methods of WSASW have given the most accurate settlement predictions as compared to the other traditional methods employed in this study. The shear wave velocity is the most significant parameter in the sensitivity analysis compared to the damping and density which are required parameters in the seismic settlement formula.

REFERENCES

Bjerrum, L. 1972, Embankment on Soft Ground, 5th PSC, ASCE, vol. 2, pp. 1-54.

Brown, P. T. & Gibson, R. E. 1972. Surface settlement of a deep elastic stratum whose modulus increases linearly with depth. Can. Geotech. J. 9,467-476.

Coduto, D. P. 1994, Foundation Design: Principle and Practices, Prentice Hall, New Jersey, 796 pp.

Herrmann, R.B. 1994. Computer Programs in Seismology, User's Manual, St.Louis University, Missouri, USA.

Kim, D.-S. & Park, H.-C. 2002. Determination of Dispersion Phase Velocities for SASW method Using Harmonic Wavelet Transform, Soil Dynamics and Earthquake Engineering, Vol.22, No.8, (September 2002), pp.675-684.

Rosyidi, S.A.P 2009. Wavelet Analysis of Surface Wave for Evaluation of Soil Dynamic Properties, Ph.D. Thesis, the National Universiti of Malaysia, Bangi.

Shokouhi, P., Gucunski, N. & Maher, A. 2003. Application of Waveles in Detection of Cavities under Pavements by Surface waves, Transportation Research Record No.1860, pp. 57-65.

Stokoe II, K.H., Wright, S.G., Bay, J.A. & Röesset, J.M. 1994. Characterization of Geotechnical Sites by SASW Method. In Geophysical Characterization of Sites, R.D. Woods (Ed.), 15-25,Oxford Publishers, New Delhi.

Terzaghi, Karl and Peck, Ralph B. 1967. Soil Mechanics in Engineering Practice, 2nd Ed. John Wiley, New York.

Torrence, C. & Compo, G.P. 1998. A Practical Guide to Wavelet Analysis, Bulletin of the American Meteorological Society, Vol.79, No.1, (January 1998), pp. 61-78.

LongTerm Settlement by Seismic

ORIGINALITY REPORT

17%	%	17%	%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Sri Atmaja P. Rosyidi, Mohd. Raihan. "Chapter 7 Wavelet Spectrogram Analysis of Surface Wave Technique for Dynamic Soil Properties Measurement on Soft Marine Clay Site", InTech, 2012 Publication	13%
2	Rosyidi, Sri Atmaja P.. "Use of Wavelet Analysis and Filtration on Impulse Response for SASW Measurement in PCC Slab of Pavement Structure", Contemporary Topics on Testing Modeling and Case Studies of Geomaterials Pavements and Tunnels, 2011. Publication	2%
3	A Kareem, T Kijewski. "Time-frequency analysis of wind effects on structures", Journal of Wind Engineering and Industrial Aerodynamics, 2002 Publication	1%
4	Mohamad Nor Omar, Colin Peter Abbiss, Mohd. Raihan Taha, Khairul Anuar Mohd. Nayan. "Prediction of long-term settlement on soft clay using shear wave velocity and damping characteristics", Engineering Geology, 2011 Publication	1%
5	Rosyidi, Sri Atmaja P., and Mohd.Raihan Taha. "Coupled Procedure for Elastic Modulus and Damping Ratio Measurement on Pavement Subgrade Structures Using Surface Wave Method", Contemporary Topics on Testing Modeling and Case Studies of Geomaterials	<1%